The missing metals problem: II. How many metals are in $z \simeq 2.2$ galaxies?

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ABSTRACT

In the context of the "missing metals problem", the contributions of the UV-selected $z \simeq 2.2$ "BX" galaxies and $z \simeq 2.5$ "distant red galaxies" (DRGs) have not been discussed previously. Here we show that: (i) DRGs only make a marginal contribution to the metal budget ($\sim 5\%$); (ii) BX galaxies contribute as much as 18% to the metal budget; and (iii) the K-bright subsample ($K < 20$) of the BX sample (roughly equivalent to the 'BzK' selected samples) contributes roughly half of this 18%, owing both to their larger stellar masses and higher metallicities, implying that the rare K-bright galaxies at $z > 2$ are a major source of metals in the budget. We showed in the first paper of this series that submm galaxies (SMGs) brighter than 3 mJy contribute $\sim 5\%$ ($\lesssim 9\%$ as an upper limit) to the metal budget. Adding the contribution of SMGs and damped Lyα absorbers, to the contribution of UV selected galaxies, implies that at least 30% of the metals (*in galaxies*) have been accounted for at $z \simeq 2$. The cosmic metal density thus accounted for is $\rho_{Z,\text{galaxies}} \simeq 1.3 \times 10^6$ M$_\odot$ Mpc^{-3} or in terms of the closure density, $\Omega_Z = 9.6 \times 10^{-6}$. This is a lower limit given that galaxies on the faint-end of the luminosity function are not included. An estimate of the distribution of metals in local galaxies as a function luminosity suggests that galaxies with luminosity $< L^\star$ contribute about half of the total mass of metals. If the metals in galaxies at z∼2 are similarly distributed then faint galaxies alone cannot solve the 'missing metals problem.' Galaxy populations at z∼2 only account for about 50% of the total metals predicted.

Key words: cosmology: observations — galaxies: high-redshift — galaxies: evolution — galaxies: abundances

1 INTRODUCTION

For a given initial mass function (IMF), the total expected amount of metals $\rho_{Z,\text{expected}}$ formed at a given time t is simply the integral of the star formation history (SFH) or star formation rate density (SFRD; Lilly et al. 1996; Madau et al. 1996; Giavalisco et al. 2004; Hopkins 2004, and others): i.e., $\rho_{Z,\text{expected}} = \dot{\rho}_\star(t) \times <p_z>$, where $<p_z>$ is the mean stellar yield (Songaila et al. 1990). Madau et al. (1996) found that $<p_z> = \frac{1}{42}$ or 2.4% using a Salpeter IMF extending from 0.1 to 125 M$_\odot$ [1] and the type II stellar yields (for solar metallicity) $p_z(m)$ from Woosley & Weaver (1995). After integrating the SFH over the redshift z range from 4 to 2 (or 1.75 h_{70}^{-1} Gyr), we find that the total co-

moving metal density is:

$$\rho_{Z,\text{expected}} = 4.0 \times 10^6 \text{ M}_\odot \text{ Mpc}^{-3}, \qquad (1)$$

(Bouché et al. 2005; Pettini 2003) using the SFH parameterized (in a LCDM cosmology) either as in Cole et al. (2001) or by a constant star formation rate (SFR) beyond $z = 2$. Equation 1 is about 25% of the $z = 0$ metals.

At redshifts $z \simeq 2-3$, our knowledge of the cosmic metal budget is still highly incomplete, contrary to the situation at redshift $z = 0$ (e.g. Fukugita & Peebles 2004). Until very recently, it was thought that only a small fraction (20%) of the budget is actually accounted for when one adds the contribution of the Lyα forest ($N_{\text{H I}} = 10^{13-17}$ cm^{-2}), damped Lyα absorbers (DLAs) ($N_{\text{H I}} > 10^{20.3}$ cm^{-2}), and galaxies such as Lyman break galaxies (LBGs) (Pettini et al. 1999; Pagel 2002; Pettini 2003; Wolfe et al. 2003).

Over the last decade, numerous samples of $z > 2$ galaxies have emerged thanks to the increasing size and sensitivity of near-infrared detectors and to the availabil-

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[1] Madau et al. (1996) notes that the conversion is fairly insensitive to the IMF as long as the stellar population extends as a power law to massive stars, 50-100 M$_\odot$.

ity of ultraviolet-sensitive instruments. On the one hand, the $z = 3$ Lyman break technique (e.g. Steidel et al. 1999) was extended to lower redshifts ($z \sim 1.5$–2.5) using different $U_n G \mathcal{R}$ colour criteria (Steidel et al. 2004). Samples selected in this way are referred to as 'BX/BM' galaxies (Adelberger et al. 2004). Using near-infrared imaging to select red galaxies with $J - K_s > 2.3$ colour, the Faint Infrared Extragalactic Survey (FIRES) (Franx et al. 2003; van Dokkum et al. 2003) unveiled significant numbers of galaxies at $z \sim 2.5$ which they dubbed 'distant red galaxies' (DRGs). The FIRES near-infrared selection includes both passively evolving (PE) and reddened star-forming (SF) galaxies with $E(B-V) > 0.3$ (Förster Schreiber et al., 2004). The $K < 20$ criterion (hereafter 'K20'; Cimatti et al. 2002) and in particular the $B - z$ vs. $z - K$ colour criteria (hereafter 'BzK'; Daddi et al. [2004,2005]) also revealed a significant number of galaxies with $1.5 < z < 2.5$ with a range of star-formation histories including both SF and PE galaxies.

This paper is the second in our series to estimate the contribution of various galaxy populations at $z \sim 2$ to the total metal budget. In Bouché et al. (2005) (paper I), we showed from current observations of $z \simeq 2$ submm galaxies (SMGs) that SMGs (brighter than 3 mJy) contain $\sim 5\%$ (and certainly $\lesssim 9\%$) of the metal budget at $z \simeq 2$. In this paper, we discuss the contribution of $z \simeq 2.2$ colour selected galaxies to the metal budget. We will show that colour selected galaxies ('BX' galaxies) contribute significantly ($\sim 18\%$) to the metal budget. The K-bright ($K_s < 20$, hereafter BX+K20) subsample contributes 8% to the metal budget, or almost half of the 18%. Since these samples are all magnitude limited, we discuss likely contribution of the sample of galaxies at $z \sim 2$ if one considers the faint end of the luminosity function using the metal-luminosity relation in local galaxies. Such an analysis suggests that galaxy populations at $z \sim 2$ only contribute about 50% to the total metal budget. In paper III, we will explore whether the remaining metals have been expelled from small galaxies into the intergalactic medium (IGM).

In the remainder of this paper, we used $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $H_o = 70\ h_{70}\ \mathrm{km\,s^{-1}\ Mpc{-}1}$ and $h = h_{100}$.

2   THE METAL BUDGET AT $Z \sim$2.2

2.1   The contribution of 'BX' galaxies

Using colour selection criteria similar to those of $z = 3$ LBGs, Steidel and collaborators have constructed large samples of galaxies at $z \simeq 2.2$ (BX) and 1.7(BM). The median redshifts of these samples are 2.22 ± 0.34 (BX), and 1.70 ± 0.34(BM), respectively (e.g. Adelberger et al. 2004).

The observed number density of BX and BM galaxies ($n_{\mathrm{BX/BM}}$) is somewhat higher than $z = 3$ LBGs. Indeed, according to Adelberger et al. (2005), $n_{\mathrm{BX}} = (6 \pm 3) \times 10^{-3}\ h_{100}^3\ \mathrm{Mpc^{-3}}$, and $n_{\mathrm{BM}} = (5 \pm 2.5) \times 10^{-3}\ h_{100}^3\ \mathrm{Mpc^{-3}}$, whereas $n_{\mathrm{LBG}} = (4 \pm 2) \times 10^{-3}\ h_{100}^3\ \mathrm{Mpc^{-3}}$. We summarize these numbers in Table 1 for h_{70}.

Shapley et al. (2005) derived the stellar masses ($M_\star$) of 72 spectroscopically-confirmed $z = 2.2 \pm 0.3$ galaxies using UV to mid-IR observations. The mean $M_\star$ of their sample is $< \log M_\star >= 10.3 \pm 0.5$ for a Salpeter IMF extending from 0.1 to 100 $\mathrm{M_\odot}$.

The last piece of information needed to estimate the contribution of the BX galaxies to the metal budget is their metallicity. Few BXs have had their gas phase metallicities published. For instance, Shapley et al. (2004) found that the metallicities of 7 BX galaxies are close to solar, but the median of a much larger sample appears to be about half solar (Pettini 2005).

Using these estimates, we find that BX galaxies contribute:

$$\rho_{Z,\mathrm{BX}} \simeq 3.8 \times 10^5\ \frac{<Z>}{0.5\,Z_\odot}\ \mathrm{M_\odot}\ \mathrm{Mpc^{-3}} \qquad (2)$$

to the cosmic metal density or about 10% of the expected metal density at $z \sim 2$ (equation 1).

BX galaxies with K-band magnitudes brighter than 20 (hereafter BX+K20) appear to be more evolved systems. Indeed, they seem to have higher stellar masses [$< \log M_\star >= 11 \pm 0.6$, Shapley et al. (2005)], and are more metal rich: their median metallicity is slightly below solar [$Z \sim 4/5 Z_\odot$, Pettini (2005)]. However, they are significantly rarer: their number density is a factor of 10 lower [$n \sim 1.7 \times 10^{-4}\ h_{70}^3\ \mathrm{Mpc^{-3}}$, Shapley et al. (2005)]. The outcome is that K_s-bright BX galaxies contribute significantly to the metal budget:

$$\rho_{Z,\mathrm{BX,K<20}} \simeq 3.0 \times 10^5\ \frac{<Z>}{0.8\,Z_\odot}\ \mathrm{M_\odot}\ \mathrm{Mpc^{-3}} \qquad (3)$$

or 8% of the estimated total metal density (equation 1). These numbers are summarized in Table 1.

Unlike for the SMGs in paperI, we have not applied a correction for the "duty cycle", the fraction of cosmic time over which they meet the observational selection criteria. The duty cycle of BXs can be estimated from the comparison of the clustering strength to the observed number density (Adelberger et al. 2005). Adelberger et al. (2005) find that the duty cycle for the "BM/BX" galaxies is ~ 1.0, suggesting no correction to our estimate is required.

2.2   The contribution of DRGs

Red near-infrared colour selection of galaxies (such as DRGs with $J - K_s > 2.3$ Franx et al. 2003; van Dokkum et al. 2003) was designed to discover large numbers of $z \sim 2.5$ evolved galaxies with a strong Balmer break. DRGs are massive galaxies and include both heavily reddened SF galaxies, and PE galaxies (Förster Schreiber et al., 2004; Labbé et al. 2005).

The space density of DRGs is about $1 \times 10^{-4}\ h_{70}^3\ \mathrm{Mpc}$ (Labbé et al. 2005; Reddy et al. 2005). Förster Schreiber et al., (2004) found, from modelling the spectral energy distributions (SEDs) of DRGs, that their mean stellar mass is about 5 times higher than $z \sim 3$ LBGs, or $M_\star \simeq 1 \times 10^{11}\ \mathrm{M_\odot}$(for a Salpeter IMF between 0.1 and 100 $\mathrm{M_\odot}$) and only varies by a factor of ~ 2 depending on the star formation history assumed.

van Dokkum et al. (2004) estimated the metallicity of a couple of DRGs from Keck NIRSPEC spectra. They found that the metallicities, as determined using $[NII]/\mathrm{H}\alpha$, are high, 1-1.5 times the solar value. From the long slit kinematics, van Dokkum et al. (2004) estimated that the dynamical masses are about $\sim 1 \times 10^{11}\ \mathrm{M_\odot}$, in agree-

ment with the mass estimates using the SED modelling of Förster Schreiber et al., (2004).

Based on these published results, we find that the cosmic metal density contributed by DRGs is:

$$\rho_{Z,\mathrm{DRGs}} \simeq 2 \times 10^5 \, \frac{<Z>}{1\,\mathrm{Z}_\odot} \, \mathrm{M}_\odot \, \mathrm{Mpc}^{-3} \qquad (4)$$

or 5% of the expected metal density (equation 1).

3   DISCUSSION & CONCLUSIONS

Table 1 summarizes the observations discussed here. The properties of $z = 3$ LBGs are listed for comparison.

From the observations discussed above, we find that the metal density in BX galaxies is:

$$\rho_{Z,\mathrm{BX}} = 3.8 \times 10^5 \, \frac{<Z>}{0.5Z_\odot} \mathrm{M}_\odot \, \mathrm{Mpc}^{-3} \, , \qquad (5)$$

or 10% of the metal budget, assuming a mean metallicity $<Z>$ of one-half solar and the above co-moving space densities.

The more evolved sub-sample of the BX sources, namely BX+K20 galaxies, are rarer (by a factor of 10), but more massive (by a factor of 5), and more metal rich (by a factor of 2). Thus, they double the total contribution of 'BX' galaxies to the metal budget. The metal density of this subsample is:

$$\rho_{Z,\mathrm{BX+K20}} = 3.0 \times 10^5 \, \frac{<Z>}{4/5Z_\odot} \mathrm{M}_\odot \, \mathrm{Mpc}^{-3} \qquad (6)$$

or 8% of the metal budget. Thus, the rare K-bright galaxies at $z > 2$ are a major source of metals in the budget. We are still far from closing the metal budget however. If we take these numbers at face-value, as much as 18% of the metals could be in BX galaxies.

Regarding the 'BzK' selection of $z \sim 2$ galaxies by Daddi et al. (2004), we note that the mean redshifts for BzK/SF (star-forming) galaxies and BzK/PE (passive evolving) galaxies is $<z> \simeq 2 \pm 0.3$ and 1.7 ± 0.2, respectively (Reddy et al. 2005). Focusing on the $z > 2$ subsample (i.e., BzK/SF), Reddy et al. (2005) showed that the 'BX' selection criteria and that the 'BzK/SF' selection criteria overlap significantly ($\sim 80\%$) to $K_s = 22$. We therefore view these two populations (BX and BzK/SF) as two strongly overlapping samples which do not require separate analyses of their contribution to the metal budget at z$\sim$2.

Having now considered a substantial number of samples of galaxies selected at z$\sim$2, we can now estimate the total metal budget in galaxies. We have estimated that 5% ($\lesssim 9\%$) of the metals are in $z \sim 2.4$ SMGs (brighter than 3 mJy; as shown in paper I), 18+5% in UV-selected and $J - K$-selected galaxies, and 5% in DLAs (Pettini et al. 2003, and the forthcoming paper III). The resulting sum is:

$$\rho_{Z,\mathrm{galaxies}} \simeq 1.3 \times 10^6 \, \mathrm{M}_\odot \, \mathrm{Mpc}^{-3} \qquad (7)$$

or $\sim$33% of the expected metal density at $z \simeq 2$ (equation 1) [2].

However, equation 7 is a lower limit given that we really

only considered the bright end ($\gtrsim$L$_\star$) of the galaxy luminosity function. One obvious criticism of our approach is that given the limited depth of the selection images and the obvious incompleteness, could the metals hide in low luminosity/low mass galaxies? While it is difficult to estimate what the contribution of the faint end of the luminosity function might be to the total metal budget, perhaps considering the local population of galaxies might be useful as a guide. In the local Universe, while galaxies at the faint-end of the luminosity function are more numerous than the luminous galaxies, they are also more metal-poor (e.g., Tremonti et al. 2004).

For the local Universe, we estimate the contribution of the faint-end of the luminosity function $\phi(L)$ using the well-known luminosity-metallicity (LZ) relation (e.g. Tremonti et al. 2004; Garnett 2002). Using mass-to-light ratios $[M/L(L)]$ from Kauffmann et al. (2003), the $z = 0$ LZ relation ($O/H(M)$ or $Z(M)$) from Garnett (2002) and $\phi(L)$ from Driver et al. (2005), one can estimate the cumulative metal density ($\int \phi(L)M/L(L)Z(M)$). Fig. 1 shows the cumulative Oxygen density $M(O)$ at $z = 0$. The right axis shows the total metal density $M(Z)$. The 5th, 50th and 90th percentiles are shown. From Fig. 1, one sees that, at $z = 0$, 50% of the metals are in galaxies fainter than $L_\star$. Note that the metal density reaches $\sim 2 \times 10^7$ M$_\odot$ Mpc^{-3}, close to the metal density obtained from integrating the SFH down to $z = 0$, i.e. $\rho_{Z,z=0} = 1.8 \times 10^7$ M$_\odot$ Mpc^{-3}, showing that the normalization must be approximately correct. Constraints on the LZ relation at $z > 2$ are just becoming available (Savaglio et al. 2005; Erb et al. 2005, C.C. Steidel, private communication).

Based on these local results, at least 50% of the metals in galaxies are in objects on the faint-end of the luminosity function (L$\lesssim$L*). The limiting depths of the surveys that find z$\sim$2 galaxies reach to or even beyond L*. If we assume for simplicity that our numbers and estimates are appropriate for L* and more luminous galaxies and that the z$\sim$2 galaxies have a similar relative fraction of metals above and below L*, it would suggest that we need to correct our total metal estimate by about a factor of 2. This is likely an overestimate of the true correction necessary for the faint end of the luminosity function and shows that the total contribution to the metal budget is roughly 60% or less. In addition, this sum might also count some of the galaxy types twice, given that we effectively extrapolate to the faint end of the LF for each of the samples. Given these caveats, one can easily account for ~ 30—60% of the metal budget. We will discuss in paper III the possibility that the remaining missing metals could have been ejected from small galaxies via galactic outflows into the IGM.

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[2] We note that at $z \sim 3$, the "missing metals problem" likely remains more acute. Unlike the "BM/BX" galaxies, LBGs only contribute about 5-10% of the total metals at z$\sim$3.

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Table 1. Summary of properites of $z > 2$ galaxies. References: (a) Adelberger et al. (2005), (b) Pettini (2005), (c) Shapley et al. (2005), (d) Pettini et al. (2001) (e) Shapley et al. (2004), (f) Reddy et al. (2005), (g) Labbé et al. (2005), (h) Förster Schreiber et al., (2004), (i) van Dokkum et al. (2004).

	$< z >$	$n\ (h_{70}^3\ \mathrm{Mpc}^{-3})$ 10^{-3}	$Z/Z_\odot$	$M_\star\ (\mathrm{M}_\odot)$ 10^{10}	$\rho_Z\ (M_\odot\ \mathrm{Mpc}^{-3})$ 10^5	Ω_Z 10^{-6}
BX	2.2 ± 0.3	2 ± 1 [a]	0.5 [b]	2 [c]	3.8	2.8
BX+K20	2.2 ± 0.3	0.2 [c]	0.8 [b]	10 [c]	3.0	2.2
DRGs	2.5 ± 0.4	0.1 [f,g]	1.0 [i]	10 [h]	1.9	1.4
LBGs	3.0 ± 0.3	1.3 ± 0.7 [a]	0.33 [d]	1.2 [e]	3.0	2.2
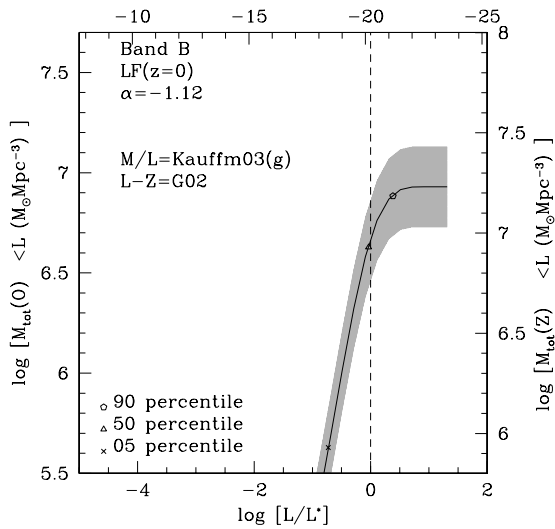
Figure 1. The cumulative Oxygen cosmic density using the $z = 0$ luminosity function from Driver et al. (2005), the LZ relation from Garnett (2002) and the M/L from Kauffmann et al. (2003). The right-axis shows the cosmic metal density. The 5th, 50th and 90th percentiles are shown as a cross, triangle and circle respectively. Because of the very opposite slopes of the LF and of the LZ relation, the 50th percentile arises at around $L \simeq L_\star$. As a consequence, 50% (or more) of the metal budget lies in the faint end of the LF. Note that the metal density reaches $\sim 2 \times 10^7$ $\mathrm{M}_\odot$ Mpc^{-3}, close to the metal density obtained from integrating the SFH, i.e. 1.8×10^7 $\mathrm{M}_\odot$ Mpc^{-3}, showing that the normalization appears to be correct.

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